Energy 35 (2010) 2580–2586

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A study on torrefaction of various biomass materials and its impact on lignocellulosic structure simulated by a thermogravimetry

Wei-Hsin Chen*, Po-Chih Kuo

Department of Greenergy, National University of Tainan, Tainan 700, Taiwan, ROC

ARTICLE INFO

Article history:
Received 26 November 2009
Received in revised form
26 January 2010
Accepted 28 February 2010
Available online 1 April 2010

Keywords:
Light and severe torrefaction
Pyrolysis
Thermogravimetric analysis (TGA)
Thermal decomposition
Lignocellulosic structure
Biomass

ABSTRACT

Torrefaction processes of four kinds of biomass materials, including bamboo, willow, coconut shell and wood (Ficus benjamina L.), were investigated using the thermogravimetric analysis (TGA). Particular emphasis is placed on the impact of torrefaction on hemicellulose, cellulose and lignin contained in the biomass. Two different torrefaction processes, consisting of a light torrefaction process at 240 °C and a severe torrefaction process at 275 °C, were considered. From the torrefaction processes, the biomass could be divided into two groups; one was the relatively active biomass such as bamboo and willow, and the other was the relatively inactive biomass composed of coconut shell and wood. When the light torrefaction was performed, the results indicated that the hemicellulose contained in the biomass was destroyed in a significant way, whereas cellulose and lignin were affected only slightly. Once the severe torrefaction was carried out, it further had a noticeable effect on cellulose, especially in the bamboo and willow. The light torrefaction and severe torrefaction were followed by a chemically frozen zone, regardless of what the biomass was. From the viewpoint of torrefaction application, the investigated biomass torrefied in less than 1 h with light torrefaction is an appropriate operation for producing fuels with higher energy density.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Biomass energy or bioenergy is an important energy resource in the world and it has been extensively employed in underdeveloped, developing and developed countries. In fact, according to the statistics of International Energy Agency (IEA) [1], biomass and waste account for around 10% of the primary energy demand worldwide in 2005. To develop bioenergy from biomass, a variety of conversion techniques such as physical, thermal, chemical and biological methods have been utilized [2]. In these methods, the thermal conversion is the most commonly used technique. Conventionally, combustion, gasification and pyrolysis of biomass [3–6] as well as co-firing of biomass and coal [7,8] have been widely applied for the purpose of getting heat, power, synthesis gas (or syngas) and biofuels, etc. Before these methods are carried out, it is desirable to decrease the moisture in fuels. In general, the less moisture contained in biomass, the higher the conversion efficiency. Regarding the particle size, in some reactors the fuel has to be greatly meshed to facilitate reaction. For instance, coal is always grinded into the form of pulverized coal before it is used in entrained-bed gasifiers or blast furnaces [9,10].

Generally speaking, the moisture contained in raw biomass is high, whereas the energy density of the raw biomass is low compared to that of fossil fuels. This results in that the applications of raw biomass in industry are restricted and it is difficult to comminute the biomass into small particles. Besides, raw biomass is generally hygroscopic so that it cannot be stored for a long time and the utilization efficiency of biomass is relatively lower. Torrefaction is a mild pyrolysis process. In this process, raw biomass is heated at an inert or nitrogen atmosphere with the temperature in the range of 225–300 °C [11–13]. After undergoing torrefaction, the moisture contained in the biomass is substantially reduced and the components of low weight organic volatile are liberated. As a result, hydrophobic solids with higher content of fixed carbon are produced [14]. This implies, in turn, that the energy density of the torrefied biomass is enlarged and the grindability of the solids is improved greatly. For example, in the studies of Bergman et al. [15,16], it was reported that electricity consumption for size reduction of torrefied wood was reduced 50–85% when compared to that of fresh wood.

In recent years, torrefaction of lignocellulosic biomass has attracted more interest in research resulting from its potential applications. In order to recognize the role played by torrefaction in

---

* Corresponding author. Tel.: +886 6 2605031; fax: +886 6 2602205.
E-mail address: weihsinchen@gmail.com (W.-H. Chen).

0360-5442/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2010.02.054

Table 1
Proximate and elemental analyses as well as heating values of four tested biomass materials.

		Bamboo	Willow	Coconut shell	Wood (Ficus benjamina L.)
Proximate analysis (wt %)	Moisture	16.86	2.27	12.86	2.54
	VM	63.54	78.91	63.76	77.13
	FC	12.85	16.05	15.58	8.98
	Ash	6.75	2.77	7.78	11.35
Elemental analysis (wt %, dry basis)	C	44.62	47.20	44.69	43.43
	H	5.54	5.86	5.47	5.51
	N	8.76	3.52	9.57	9.85
	O	41.08	43.42	40.27	41.21
Fiber analysis (wt %)	Hemicellulose	33.30	20.06	21.03	25.91
	Cellulose	10.91	59.72	41.84	48.89
	Lignin	55.79	20.22	39.17	25.50
HHV (MJ/kg, dry basis)		17.32	18.37	17.66	16.39

improving the properties of biomass, a number of studies have been implemented. For instance, Arias et al. [17] studied the impact of torrefaction on the grindability and reactivity of wood biomass used in pulverized systems. They found that, after the torrefaction of eucalyptus at 240 °C for 30 min, the grinding characteristics of the biomass were apparently improved. Moreover, around 90% of heating value yield in contrast to the raw biomass was attained. Deng et al. [18] torrefied rice straw and rape stalk to evaluate the pretreatment of torrefaction for co-gasification. They reported that the heating values of the torrefied rice straw and rape stalk could be increased up to 17% and 15%, respectively, compared to those of the raw materials. The properties of the torrefied agricultural residues were closer to that of coal; therefore, torrefaction was a promising method for biomass to combine with coal co-gasification. By employing wet torrefaction (hot compressed water) and dry torrefaction (nitrogen), Yan et al. [19] investigated the thermal behavior of loblolly pine. It was described that the energy density of the pretreated biomass could be increased by 8–36%, depending on the torrefaction conditions. Meanwhile, the wet torrefaction process produced a solid with greater energy density than the dry torrefaction at the same mass yield. Couhert et al. [20] evaluated the impact of torrefaction on the production of syngas from wood gasification in an entrained flow reactor. Seeing that the torrefaction decreased the O/C ratio of the biomass, the quantity of the produced syngas increased with the severity of the torrefaction.

Reviewing the recent literature suggests that torrefaction is a promising technique to improve the performance of biomass for energy utilization. Despite a number of impressive studies implemented as described above, there still remains a lot of torrefaction information that is not recognized in sufficient detail. In the present study, the torrefaction characteristics of four different biomass materials will be explored using a thermogravimetric analyzer. Biomass torrefaction is normally performed in an oven filled with nitrogen. Though the samples used in a thermogravimetry are much less than those in an oven, the reaction environments are similar to each other. On the other hand, the advantage of torrefaction analyzed in a thermogravimetric analyzer is that the weight loss process of biomass can be measured precisely. For this reason, biomass torrefied in a thermogravimetric analyzer is carried out in the present study. Emphasis is particularly placed on the impact of the torrefaction on the lignocellulosic structures and pyrolysis processes of the biomass materials. A light and a severe torrefaction processes will be considered to account for the effect of the temperature on the torrefaction results.

2. Experimental

Four types of biomass obtained in Taiwan were selected as the raw materials to be tested; they were bamboo, willow, coconut shell and wood (Ficus benjamina L.). The proximate, elemental and fiber analyses as well as heating values (dry basis) of the four materials are listed in Table 1. The values of the proximate analysis were obtained in accordance with the procedure of American Society for Testing and Materials (ASTM). After the analyses were finished, prior to performing the thermogravimetric analyses (TGAs) of the raw materials, they were dried in an oven with the temperature of 60 °C for 24 h to provide a basis of the tested samples. After the drying procedure, the raw materials were grinded and sieved to the maximum particle size of 40 mesh (i.e. particle size $\leq$ 0.42 mm). Then, the prepared raw materials were placed in plastic bags and stored in a desiccator at room temperature until the analyses were carried out. The pyrolysis and torrefaction characteristics of the four biomass materials were analyzed using a thermogravimetry (TG, PerkinElmer Diamond TG/DTA). A crucible loaded with biomass particles was placed inside the TG where the weight was constantly measured. The functions of the TG were to measure and record the dynamics of biomass weight loss with increasing temperature or time. For all the experimental runs, around 5 mg of sample was used and the heating temperature in the TG ranged from 25 °C to 800 °C. The temperature in the TG was detected and recorded at a frequency of 2 Hz, that is, 120 temperatures were detected and recorded per minute. Nitrogen was used as a carrier gas in the TG so that the biomass was pyrolyzed in an inert environment without oxygen. The flow rate of the carrier gas was fixed at 200 cc (STP) min^{-1}. When the pyrolysis of the biomass was carried out alone, the heating rate of the TG was controlled at 20 °C min^{-1}. Alternatively, when the torrefaction was performed, a temperature program, consisting of a dynamic heating period, an isothermal heating period and a dynamic heating period, was applied. Specifically, the temperature of the TG was raised from 25 °C to the torrefaction temperature (i.e. 240 or 275 °C) with the heating rate of 20 °C min^{-1}. Once the TG reached the torrefaction temperature, the biomass was torrefied for 2 h followed by pyrolysis with the heating rate of 20 °C min^{-1} again. From the recorded distribution of the weight loss, one was able to obtain the thermogravimetric analysis (TGA) and derivative thermogravimetric (DTG) analysis. To ensure the measured quality of the study, the TG was periodically calibrated using indium (In) and tin (Sn). A calcium oxalate (CaC_2O_4) sample was also employed in the TG to check its distribution of weight loss. It suggested that the TG was able to provide accurate measurements.

3. Results and discussion

3.1. Pyrolysis of biomass

Thermogravimetric analyses of the four biomass materials are first displayed in Fig. 1 where the pyrolysis reactions without torrefaction were executed. The TGA curve represents the instantaneous weight percentage of the tested material in contrast to the initial weight. As a whole, the curves can roughly be divided into three different regions, regardless of what materials are tested. For the temperature below 200 °C (i.e. the first stage), the slight decay of the biomass weight is due to the drying procedure and the release of some light volatiles. In this stage, the weight loss of the tested material is less than 10%. When the temperature is between 200 and 500 °C (i.e. the second stage), a significant drop in weight is observed, stemming from the thermal decomposition of hemicellulose, cellulose and lignin. Details of the thermal decomposition of the three components will be described below. In this stage, the

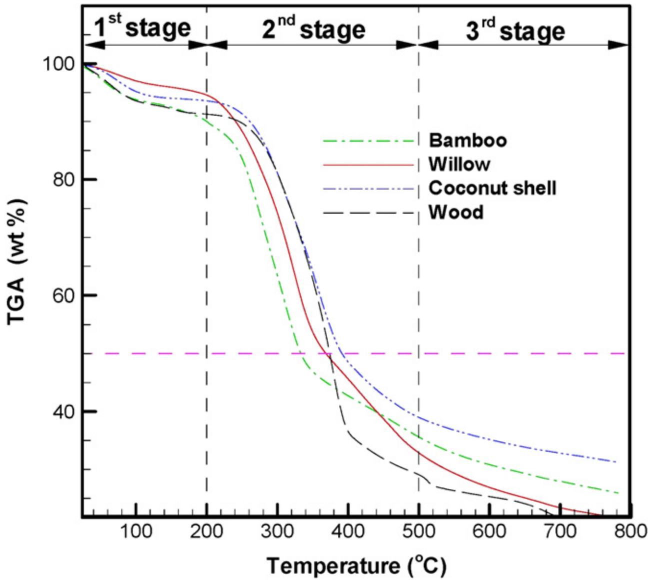

Fig. 1. Distributions of TGA of four tested biomass in a pyrolysis environment.

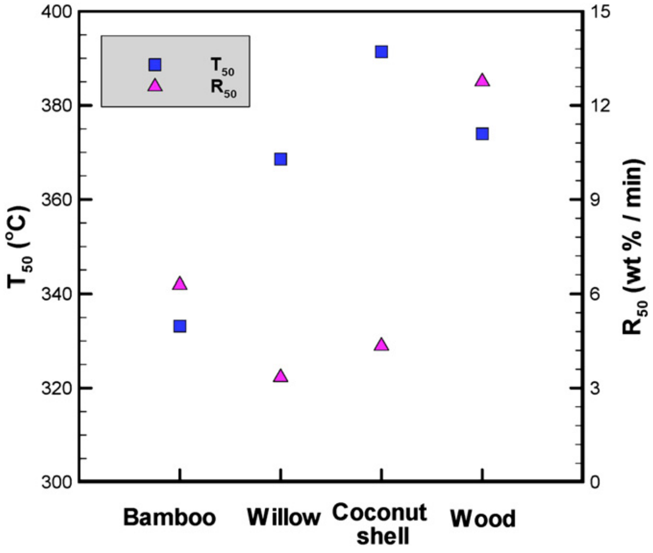

Fig. 2. Profiles of T_{50} and R_{50} of four tested biomass in a pyrolysis environment.

weight of the tested materials has been reduced to below 40%. Once the temperature is higher than 500 °C (i.e. the third stage), the weight loss is not as significant as the previous period, mainly as a consequence of thermal decomposition of other heavy components.

To provide a comprehensive comparison of weight loss between the four biomass materials, two indicators of T_{50} and R_{50} [21,22], accounting for the temperature and intensity of weight loss are considered and plotted in Fig. 2. The former and the latter represent the temperature at the level of 50% weight loss and the rate of weight loss at T_{50}, respectively. Physically, the biomass featured by a larger value of R_{50} means that the biomass is relatively active at T_{50}. As a whole, the value of T_{50} ranges from 333 to 391 °C, revealing that over 50% of weight is lost when the temperature is over 400 °C with the heating rate of 20 °C min^{-1}. Corresponding to T_{50}, the value of R_{50} is between 3.34 and 12.76% min^{-1}. It is noted that the R_{50} of wood is much higher than the other three species, implying that the rate of weight loss or reaction intensity of wood is relatively dramatic in the vicinity of T_{50}. This arises from the fact that the thermal decomposition of wood is characterized by a rapid decline in the second region, as shown in Fig. 1.

3.2. Characteristics of hemicellulose, cellulose and lignin

In general, lignocellulose is made up of three major constituents; they are cellulose, hemicellulose and lignin. Cellulose microfibrils are macromolecular structures composed of semicrystalline arrays of β-1,4 glucan chains associated with one another through extensive hydrogen bonding. Hemicellulose is characterized by linear polymers and they are usually substituted with other sugar side-chains to prevent the formation of crystalline structures. In regard to lignin, it is a phenolic polymer which essentially encases the polysaccharides of the cell walls, producing a strong and durable composite material resistant to enzymatic attack [23]. In the past studies [7,24], it has been recognized that the lignocellulosic structure of biomass can be qualitatively identified by means of DTG. In other words, because of intrinsic difference in the structures of hemicellulose, cellulose and lignin contained in biomass, as stated above, they may be distinguished from the distributions of weight loss intensity of biomass. In general, the thermal decomposition of hemicellulose occurs at temperatures ranging from 150 to 350 °C; cellulose is decomposed for the temperatures in the range of 275–350 °C, and lignin is featured by gradual decomposition for the temperatures between 250 and 500 °C [25,26]. The distributions of DTG of the four tested materials are examined in Fig. 3. Obviously, a double-peak distribution in the curve of bamboo is exhibited (Fig. 3a). The first peak (275 °C) and the second peak (308 °C) stand for the thermal decomposition of hemicellulose and cellulose, respectively. The curve behind the double peak is the pyrolysis of lignin whose intensity is, by far, smaller than that of the double peak. In the meantime, the bump exhibited at around 50 °C is due to the liberation of moisture from the raw materials. When willow is tested, only one peak is exhibited. The peak developed at 323 °C (Fig. 3b) stems from the thermal decomposition of cellulose and the curve of hemicellulose is almost merged by that of cellulose. Similar to the thermal behavior of lignin in bamboo, the thermal decomposition of the lignin in willow is also characterized by a flat region when the temperature is in the range of 380–470 °C. For the case of coconut shell, the peaks of hemicellulose and cellulose develop at 311 °C and 353 °C, respectively (Fig. 3c). Unlike the previous two materials, no flat region is observed behind the peak of cellulose, that is, lignin decays steadily with increasing temperature. With regard to the thermal decomposition of wood, the peak of cellulose is located at 378 °C and the peak of hemicellulose overlaps that of cellulose, resembling the behavior of willow. It is noteworthy that two small peaks are induced at the temperatures of 513 and 685 °C. This reflects that the wood includes two important components which are reactive only when the temperature is higher than 500 °C. In addition, from Fig. 3 it can be seen that a bump always develops at the temperature around 50 °C, as a consequence of moisture liberated from the biomass.

Upon inspection of the above observations, it should be pointed out that the structure of cellulose contained in the four samples are different each other, as a consequence of distinct locations of cellulose peak obtained in Fig. 3. Meanwhile, the DTG distributions also imply that the amount of hemicellulose contained in willow and wood are relatively small so that the peak of hemicellulose is merged by that of cellulose. For example, in the study of Bridgeman [27], hemicellulose and cellulose contained in willow were 14.1 and 49.3 wt%, respectively.

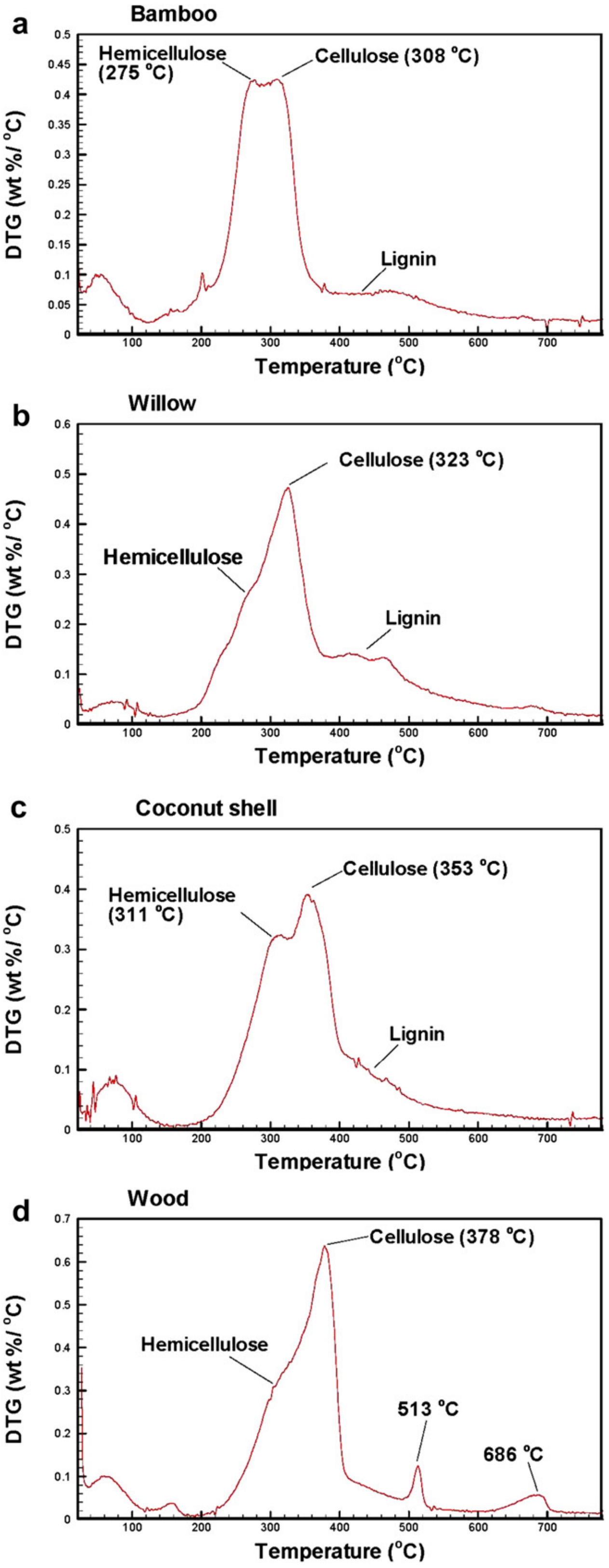

Fig. 3. Distributions of DTG of (a) bamboo, (b) willow, (c) coconut shell and (d) wood in a pyrolysis environment.

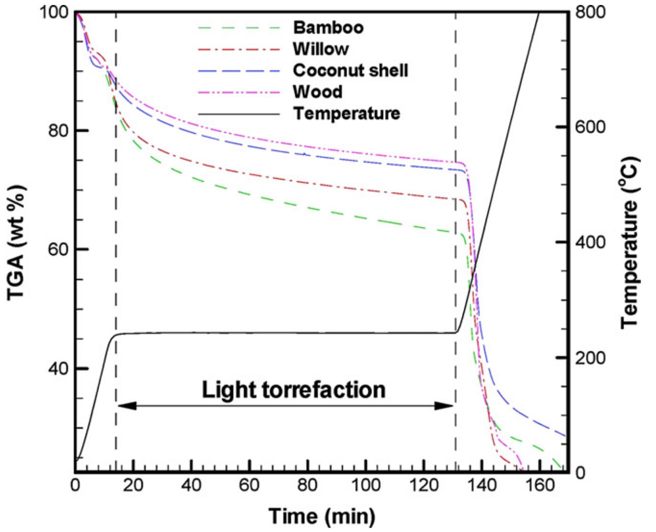

Fig. 4. Distributions of TGA of four tested biomass with light torrefaction.

3.3. Light torrefaction of the biomass materials

With attention focused on the light torrefaction processes of the four biomass species, the distributions of TGA are provided in Fig. 4. It can be found that the impact of the light torrefaction on bamboo and willow are more pronounced than that on coconut shell and wood. Specifically, after experiencing the light torrefaction, 75, 73, 68 and 63 wt% of biomass are remained in wood, coconut shell, willow and bamboo, respectively. As soon as the light torrefaction is accomplished, it can be seen that the weight keeps horizontal within a certain range of temperature, no matter what biomass is tested. This elucidates that following the light torrefaction the reaction is characterized by a chemically frozen zone. That is, almost no chemical reaction occurs during this period. Thereafter, the TGA curves commence to drop again approximately at 300 °C, depending on the types of biomass. If one further examines the DTG curves within the period of torrefaction, as shown in Fig. 5, a monotonic decrease in the distribution is exhibited, that is, the largest reaction intensity always occurs at the initial stage of the

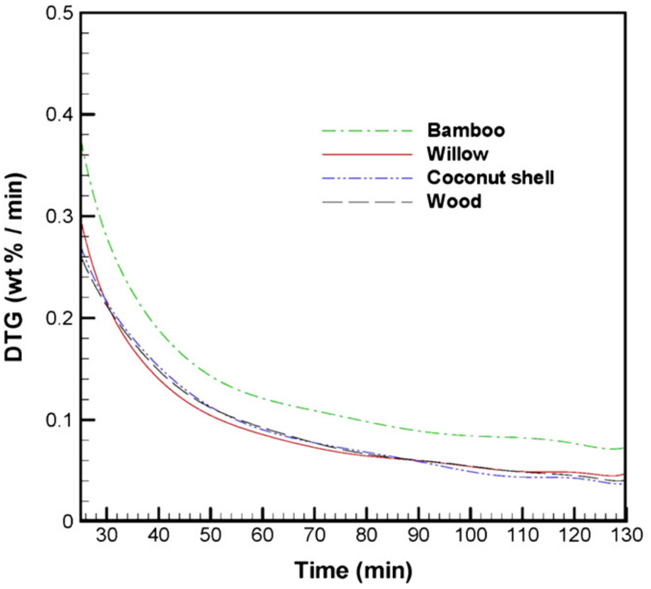

Fig. 5. Distributions of DTG of four tested biomass in the period of light torrefaction.

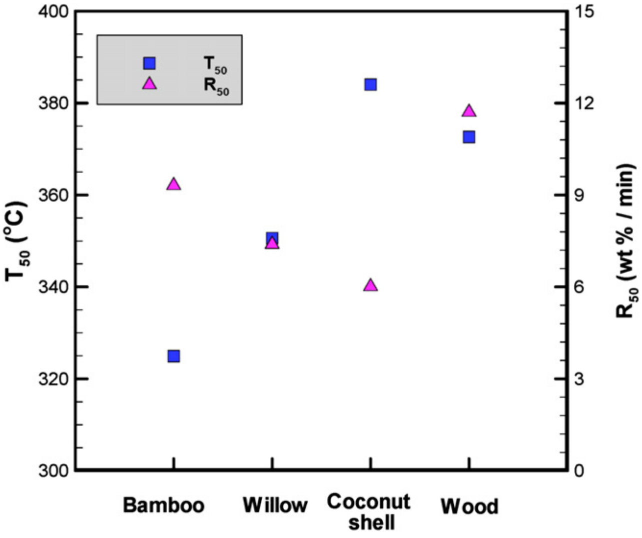

Fig. 6. Profiles of T_{50} and R_{50} of four tested biomass with light torrefaction.

torrefaction. Fig. 5 also depicts that 1 h of torrefaction is sufficiently long in that the decrement in the curves has become slight as long as the torrefaction persists over 60 min.

The values of T_{50} and R_{50} of the samples undergoing the light torrefaction are sketched in Fig. 6. As a whole, the value of T_{50} ranges from 325 to 385 °C, whereas the value of R_{50} is between 6.01 and 11.70% min^{-1}. A comparison with Fig. 2 indicates that the light torrefaction decreases T_{50} a bit; on the other hand, the reaction intensity R_{50} is enhanced to a certain extent, except for wood. If the values of R_{50} are compared with those shown in Fig. 5, it is clear that the reaction intensity of the biomass at T_{50} is larger than that in an isothermal environment approximately by an order of magnitude.

The distributions of DTG of the four samples are demonstrated in Fig. 7. In comparison to the curves shown in Fig. 3, it depicts that the peaks become sharper, especially in Fig. 7a and c where the double-peak distribution observed in Fig. 3 disappears. It follows that the light torrefaction has a drastic impact on hemicellulose. It is worthy of note that the maximum values of the cellulose peaks are slightly smaller than those shown in Fig. 3, reflecting that the cellulose contained in the samples is affected by the light torrefaction to a small extent. This illustration can also be verified from a concave up curve developed between the two peaks at 336 and 442 °C shown in Fig. 7b, resulting from the depletion of cellulose. The influence of the light torrefaction on lignin is also slight. In examining the DTG distribution shown in Fig. 7d, two small peaks develop at 512 and 690 °C, illustrating that the peaks behave as fingerprints to identify the wood.

3.4. Severe torrefaction of the biomass materials

Subsequently, the TGA distributions under the effect of severe torrefaction (275 °C) on the four types of biomass are examined in Fig. 8. In view of the higher torrefaction temperature, the drop of weight loss in the course of torrefaction is obvious, in contrast to those shown in Fig. 4. Meanwhile, it can be seen that the influence of the torrefaction on bamboo and willow are much larger than on wood and coconut shell. The aforementioned behavior can also be explained by examining the distributions of DTG shown in Fig. 9 where the initial reaction intensities of bamboo and willow are much higher than those of coconut shell and wood. At the end of the severe torrefaction, the residual weights of bamboo, willow,

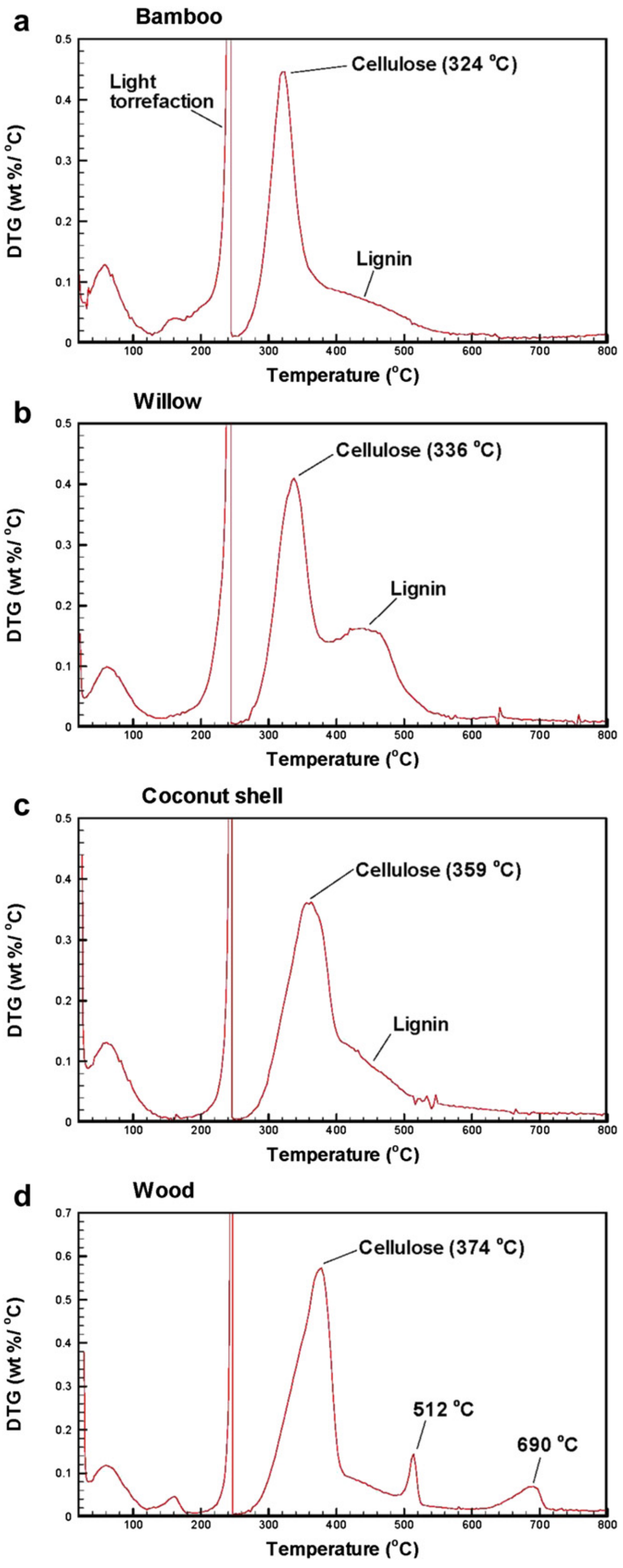

Fig. 7. Distributions of DTG of (a) bamboo, (b) willow, (c) coconut shell and (d) wood with light torrefaction.

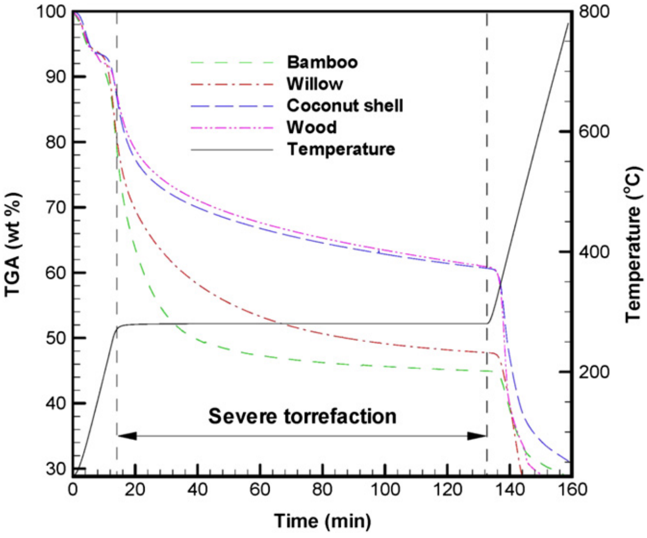

Fig. 8. Distributions of TGA of four tested biomass with severe torrefaction.

coconut shell and wood are 45, 48, 61 and 61%, respectively. Summarizing the observations in Figs. 4 and 8, two groups of the biomass materials can be partitioned. Specifically, willow and bamboo can be classified into the relatively active species, resulting from more obvious weight loss in the course of torrefaction. Alternatively, wood and coconut shell can be thought of as the relatively inactive materials, as a result of less weight loss during torrefaction. From the practical application point of view, much of the mass is lost from the raw material during the severe torrefaction, especially for bamboo and willow. Consequently, the severe torrefaction is not a recommended operation for the pretreatment of fuel from biomass. On the other hand, the interval of chemically frozen zone behind the severe torrefaction becomes wider than that following the light torrefaction (Fig. 4). It should be emphasized that, for bamboo and willow, T_{50} takes place in the period of torrefaction. In contrast, the values of T_{50} of coconut shell and wood are located at 387 and 370 °C, respectively. The values of R_{50} of coconut shell and wood are 1.72 and 7.88% min^{-1}, respectively. These two values are much smaller than those from pyrolysis (Fig. 2) and light torrefaction (Fig. 6) of the same biomass, resulting from more mass consumed within the severe torrefaction.

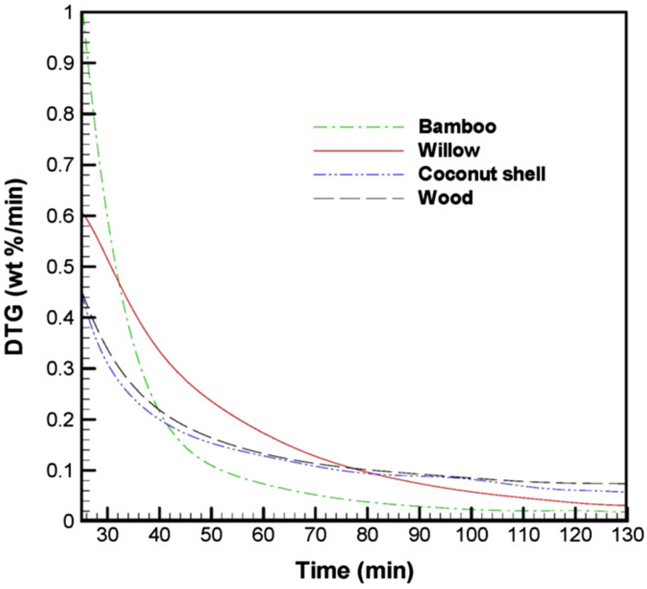

Fig. 9. Distributions of DTG of four tested biomass in the period of severe torrefaction.

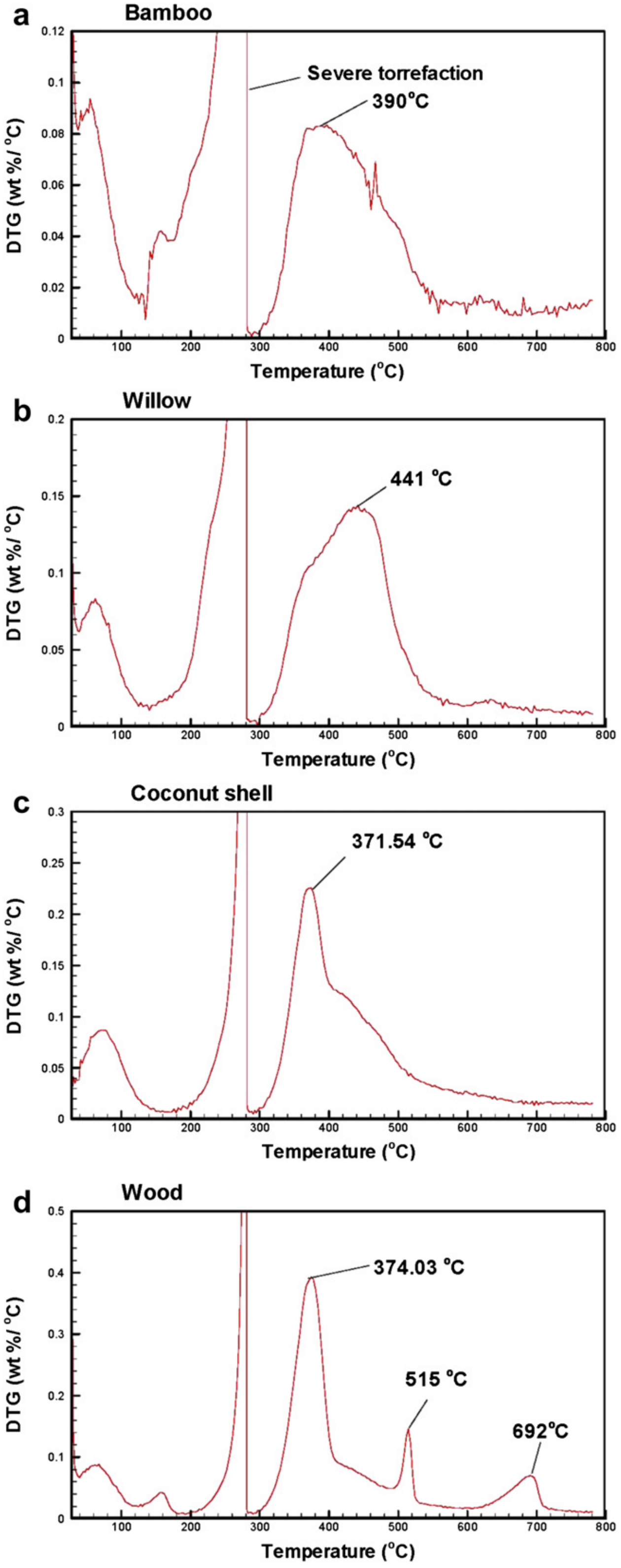

Fig. 10. Distributions of DTG of (a) bamboo, (b) willow, (c) coconut shell and (d) wood with severe torrefaction.

As far as the lignocellulosic structure of the biomass is concerned, from Fig. 10, it can be found that the peaks of cellulose of bamboo and willow wither in a significant way. Though the peaks of cellulose of coconut shell and wood are still clearly observed, the maximum values have been decreased to a certain extent. For instance, the maximum values of the peaks shown in Fig. 10c and d are 0.23 and 0.39% °C^{-1}, respectively, whereas they are 0.36 and 0.57% °C^{-1} in Fig. 7c and d, respectively. It is thus concluded that, in addition to destroying the hemicellulose, the severe torrefaction will further destroy a part of cellulose contained in the biomass, especially in bamboo and willow.

4. Conclusions

Pyrolysis, light torrefaction and severe torrefaction of four types of biomass, consisting of bamboo, willow, coconut shell and wood, have been studied to recognize the weight loss dynamics of the biomass and the impact of the torrefaction processes on the lignocellulosic structures. The obtained results suggested that the distributions of TGA and DTG were able to provide a qualitative insight into the relationship among hemicellulose, cellulose and lignin. When the pyrolysis of the biomass was performed, the weight loss process could be partitioned into three different regions, and the reactions of hemicellulose and cellulose mainly occurred at the temperatures between 200 and 400 °C. When the light torrefaction held at 240 °C or the severe torrefaction held at 275 °C was carried out, a chemically frozen zone was always exhibited after the torrefaction process was accomplished. The light torrefaction had a significant effect on the depletion of hemicellulose, but its impact on cellulose and lignin was slight. Over 60% of mass of the biomass was preserved from the light torrefaction. Therefore, the light torrefaction is a proper operation to pretreat biomass for producing fuels. When the severe torrefaction was practiced, more mass from the biomass was consumed, especially in bamboo and willow where T_{50} occurred in the course of the torrefaction. Some cellulose and lignin in the biomass were further reacted from the severe torrefaction. It is thus concluded that the severe torrefaction is not recommended to pretreat biomass for intensifying its energy density.

Acknowledgements

The authors gratefully acknowledge the financial support of National Science Council, Taiwan, ROC, on this study.

References

[1] World energy outlook. International Energy Agency; 2007.
[2] Hinrichs RA, Kleinbach M. Energy: its use and the environment. Orlando, U.S.A: Harcourt; 2006.
[3] Demirbas A. Combustion characteristics of different biomass fuels. Progress in Energy and Combustion Science 2004;30:219–30.
[4] Pröll T, Hofbauer H. H_2 rich syngas by selective CO_2 removal from biomass gasification in a dual fluidized bed system – Process modelling approach. Fuel Processing Technology 2008;89:1207–17.
[5] Demirbas A. Progress and recent trends in biofuels. Progress in Energy and Combustion Science 2007;33:1–18.
[6] Elliott DC. Historical developments in hydroprocessing bio-oils. Energy & Fuels 2007;21:1792–815.
[7] Chen WH, Wu JS. An evaluation on rice husk and pulverized coal blends using a drop tube furnace and a thermogravimetric analyzer for application to a blast furnace. Energy 2009;34:1458–66.
[8] Kalisz S, Pronobis M, Baxter D. Co-firing of biomass waste-derived syngas in coal power boiler. Energy 2008;33:1770–8.
[9] Chen WH. A simplified model of predicting coal gasification performance in a drop tube furnace. International Communications in Heat and Mass Transfer 2007;34:623–9.
[10] Du SW, Chen WH. Pulverized coal burnout in blast furnace simulated by a drop tube furnace. Energy 2010;35:576–81.
[11] Prins MJ, Ptasinski KJ, Janssen FJJG. Torrefaction of wood. Part 1. Weight loss kinetics. Journal of Analytical and Applied Pyrolysis 2006;77:28–34.
[12] Prins MJ, Ptasinski KJ, Janssen FJJG. Torrefaction of wood. Part 2. Analysis of products. Journal of Analytical and Applied Pyrolysis 2006;77:35–40.
[13] Prins MJ, Ptasinski KJ, Janssen FJJG. More efficient biomass gasification via torrefaction. Energy 2006;31:3458–70.
[14] Felfri FF, Luengo CA, Suarez JA, Beaton PA. Wood briquette torrefaction. Energy for Sustainable Development 2005;9:19–22.
[15] Bergman PCA, Boersma AR, Kiel JHA, Prins MJ, Ptasinski KJ, Janssen FJJG. Torrefaction for entrained flow gasification of biomass. In: Van Swaaij WPM, Fjallstrom T, Helm P, Grassi A, editors. Second world biomass conference. Rome, Italy: ETA-Florence and WIP-Munich; 2004. p. 679–82.
[16] Bergman PCA, Kiel JHA. Torrefaction for biomass upgrading. In: Proceedings of the fourteenth european biomass conference and exhibition, 17–21 October 2005, Paris, France.
[17] Arias B, Pevida C, Fermoso J, Plaza MG, Rubiera F, Pis JJ. Influence of torrefaction on the grindability and reactivity of woody biomass. Fuel Processing Technology 2008;89:169–75.
[18] Deng J, Wang GJ, Kuang JH, Zhang YL, Luo YH. Pretreatment of agricultural residues for co-gasification via torrefaction. Journal of Analytical and Applied Pyrolysis 2009;86:331–7.
[19] Yan W, Acharjee TC, Coronella CJ, Va squez VR. Thermal pretreatment of lignocellulosic biomass. Environmental Progress & Sustainable Energy 2009;28:435–40.
[20] Couhert C, Salvador S, Commandre JM. Impact of torrefaction on syngas production from wood. Fuel 2009;88:2286–90.
[21] Uslu A, Faaij APC, Bergman PCA. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy 2008;33:1206–23.
[22] Osório E, Gomes MLI, Vilela ACF, Kalkreuth W, Almeida MAA, Borrego AG, et al. Evaluation of petrology and reactivity of coal blends for use in pulverized coal injection (PCI). International Journal of Coal Geology 2006;68:14–29.
[23] Gomez LD, Steele-King C, McQueen-Mason SJ. Sustainable liquid biofuels from biomass: the writing's on the walls. New Phytologist 2008;178:473–85.
[24] Chen WH, Tu YJ, Sheen HK. Impact of dilute acid pretreatment on the structure of bagasse for producing bioethanol. International Journal of Energy Research 2010;34:265–74.
[25] Antal MJ. Biomass pyrolysis: a review of the literature. Part I – carbonydrate pyrolysis. Advances in Solar Energy 1983;11:61–111.
[26] Mansaray KG, Ghaly AE. Thermal degradation of rice husks in nitrogen atmosphere. Bioresource Technology 1998;65:13–20.
[27] Bridgeman TG, Jones JM, Shield I, Williams PT. Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. Fuel 2008;87:844–56.